ENHANCING RADAR INTERPRETATION AND WARNING SKILLS THROUGH ANALYSIS OF A SEVERE MCS EVENT IN KENTUCKY

ANSWER SHEET

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QUESTION SHEET 1

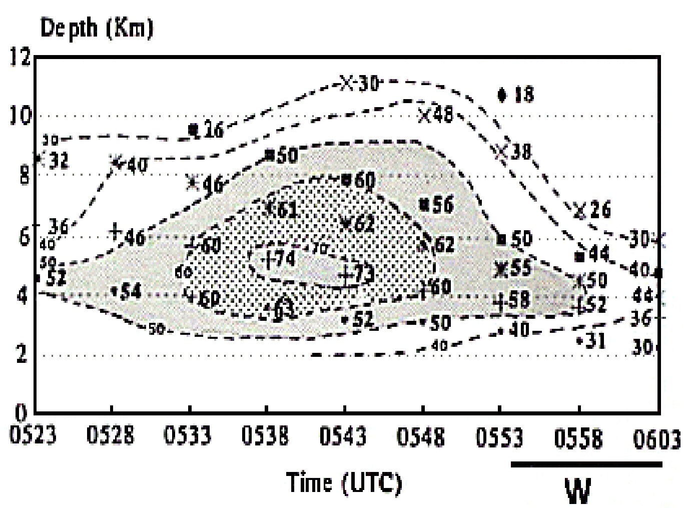
1. a) Briefly note surface, upper-air, and sounding data from 0000 UTC. b) Then consider KLVX WSR-88D data from 0528 to 0548 UTC. Note any important features in radar data. c) What type of warnings and/or statements, if any, would you issue and for what counties during this time based on your analysis? d) Based on radar trends during this period, what are your thoughts concerning the subsequent evolution of the line?

a) Environmental data at 0000 UTC 14 May 1995 showed an atmosphere that could support severe convection. At the surface, a moisture ridge axis over western Kentucky at 0600 UTC was located ahead of an approaching cold front. At 850 mb, 30-40 kt southerly flow imported dewpoints of 17 deg C into the state along a warm conveyer belt. Kentucky also was positioned within an area of upper-level divergence southeast of the highest wind core at 500 and 300 mb. Sounding data at 0000 UTC at Nashville and Little Rock revealed steep lapse rates from about 750-500 mb, above a subsidence inversion and abundant low-level moisture. Lifted indices were about -8 and CAPE values were 3800-4400 J/kg at both locations. Significant dynamic lift was present in the moist, unstable atmosphere to overcome the capping inversion. Moreover, both soundings displayed moderate-to-strong wind shear, which could act to organize convective development into a severe MCS.

b) WSR-88D base reflectivity data from 0528-0548 UTC showed a heavy rainfall producing MCS along the Ohio River west of Louisville. Deep-layered high reflectivity values (>50 dBZ) and cold cloud tops were located near the center of the MCS, although no highly reflective suspended cores were noted in the system's middle levels. By 0548 UTC, a narrow line of new cells began to form along the southern edge of the MCS from western Breckinridge to eastern Davies counties.

Storm-relative velocity map (SRM) data showed a key signature to the subsequent evolution of the MCS. A coherent and deep-layered zone of mid-altitude radial convergence (MARC) was detected at 0528 UTC within convection near the center of the MCS. At 0538 and 0543 UTC, MARC appeared on all four panels, but maximized at 2.4 deg across extreme southern Spencer county Indiana (0538) and northern Davies county Kentucky (0543), as "delta V" values reached 70-75 kts at 4.5-6 km altitude. High MARC values can be an excellent precursor signature to the subsequent onset of damaging surface winds. The cross-section below shows MARC versus time and the onset of surface wind damage (bold line with a W under it). Maximum observed MARC values preceded the onset of reported wind damage by 15-20 minutes, while *maximum* wind damage (from 0613-0633 UTC) occurred about 30-40 minutes after the period of *maximum* MARC. SRM data also suggested some rear inflow was present on the upwind portion of the MCS. This inflow may have complemented the MARC leading to an intense downdraft and subsequent wind damage.

VIL values from the storms in the MCS's center were nearly 60 kg/m^2 at 0528 UTC (highest values were 65 kg/m^2 at 0523 UTC). High VIL values and increasing MARC were noted simultaneously within the MCS. However, as MARC values peaked at 0538 and 0543 UTC, corresponding VIL values fell to 40-45 kg/m^2 at 0538 UTC and 30-35 kg/m^2 at 0548 UTC. Decreasing VIL often is interpreted as weakening convection. However, VIL trends from 0528 to 0548 UTC were deceptive in this case and not necessarily indicative that subsequent surface wind damage would occur. Lowering VIL values coincident with significant MARC should alarm forecasters that an intense downdraft from collapsing convection may result in bow echo formation and damaging downburst winds along the leading edge of the original MCS given favorable ambient conditions.



c) Strong thunderstorms were in progress from 0528-0548 UTC along the Ohio River. The strongest storms, with a deep-layered high reflectivity core and high VIL values, were over Hancock county at 0538 UTC then southern Perry and north-western Breckinridge counties by 0548 UTC (i.e., the eastern cluster of cells within the MCS). Thus, a severe thunderstorm warning was warranted for possible hail and some wind damage. The second cluster of cells over Henderson and western Davies counties at 0528 UTC also contained high VIL values. However, the convection weakened from 0528-0548 UTC as VIL values decreased (but MARC increased) over southern Spencer and northern Davies counties. This cluster was not severe during this time period, as no damage was reported in this area. However, very heavy rain and some cell training was occurring within the MCS. Therefore, the MCS needed to be monitored closely for flood potential.

Despite the weakening trend in the second cluster, the presence of strong, deep-layered MARC should send a strong signal that subsequent wind damage could occur ahead of the collapsing original cells. Indeed, a line of new cells was developing at 0548 UTC from Breckinridge to northern Ohio counties. A severe thunderstorm warning is needed for locations ahead of this intensifying line, *before* a well-defined bow echo becomes evident.

d) Forecasters need to understand the processes at work here and be able to properly anticipate subsequent convective trends. The observation of rear inflow, strong, deep-layered MARC, and decreasing VIL associated with the collapse of the original cells within a dynamic, unstable, and sheared environment strongly suggests that new convection (i.e., a bow echo) would intensify rapidly and produce major wind damage along the leading edge of the MCS. In addition, close surveillance of the bow's leading edge would be required for development of any cyclonic circulations/mesocyclones and tornadoes.

2) Starting at 0548 UTC, you are the radar operator and responsible for issuing warnings, as needed, for the event. You will be given radar data at 5 to 10-minute intervals; we also will loop reflectivity data to help visualize convective movement and trends. Based on various WSR-88D data and knowledge of the environment, specify the type of warning(s) and county(s) affected, if any. Concentrate on important radar signatures and trends for each data time, i.e., give physical reasons for your warning decisions, and write them below.

Issue Time	*Warning*	*County(s)*	*Important Radar Signatures/Trends*
0558 UTC	**Severe**	**Breckinridge, Meade**	

-A rapidly developing line of strong convection along the leading edge of the MCS was pushing eastward across Breckinridge county due to the influence of earlier MARC and rear inflow. A warning should already have been issued for this county prior to 0558 UTC. The northern/eastern cluster of convection pivoted northeastward and contained a suspended high reflectivity core aloft over Meade county along with high VIL values.

0608 UTC	**Tornado**	**Meade**
	Severe	**Hardin, northern Grayson**

-The northeastward moving convection across Meade and the line of intense storms across Breckinridge intersected near the Breckinridge/Meade county line. This intersection is an inflection point where a small-scale low center may exist with a convective-scale warm or stationary front extending east across southern Meade county and a powerful cold (gust) front extending south across eastern Breckinridge county. SRM data at 0608 UTC showed significant low-level cyclonic convergence at the intersection in northeastern Breckinridge county with rotation extending upward through at least 4.3 deg (12,000 ft). At 0.5 deg, the rotational velocity (V_r) of the vortex was about 40 kts, i.e., a "moderate" circulation. Given radar trends within the dynamic, sheared environment, a tornado warning should be issued for Meade county as the circulation/mesocyclone travels eastward along the warm/stationary boundary.

-Given a now intense bow echo with a very tight leading reflectivity gradient in Breckinridge county, a *strongly worded* severe thunderstorm warning is needed at once for Hardin county to provide lead time and to emphasize the potential for very severe wind damage from this line. Note the convergence in SRM data along the line. Northern Grayson county would get brushed by the damaging winds.

0618 UTC	**Severe**	**Jefferson**

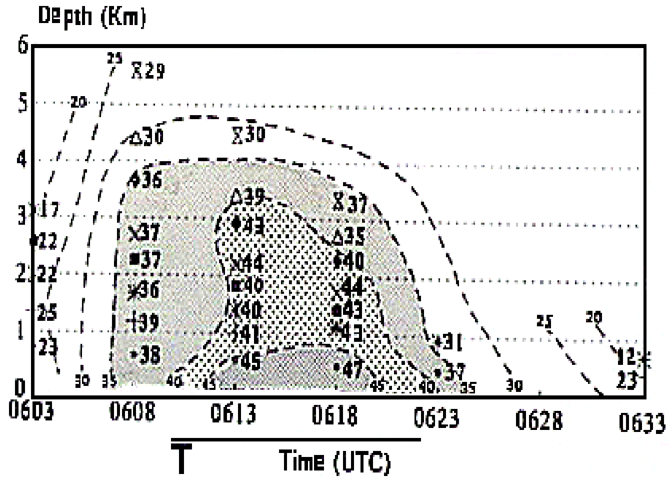
-By 0618 UTC, an organized convective-scale frontal pattern existed at 0.5 deg, with a low over Meade county at the intersection of a warm/stationary front extending east and a strong cold/gust front extending south. At this intersection, a well-defined cyclonic circulation extended up to 10.0 deg (about 11,000 ft). V_r values at 0.5 deg increased to nearly 45 kts at 0613 UTC and 50 kts at 0618 UTC, i.e., values associated with a "strong" mesocyclone. At 0618 UTC, a narrow zone of storm-relative inflow also existed along the low-level stationary front directed toward the vortex. This low-level inflow signature enhances convergence into the circulation which promotes vortex strengthening and possible tornadogenesis. An F1 tornado was reported at this location, verifying the issued tornado warning for Meade county.

-Thunderstorms along/north of the convective-scale stationary front were entering Jefferson county (just southwest of Louisville) at 0618 UTC. A deep high reflectivity core suggested that large hail and gusty winds were possible.

-Meanwhile, the apex of the very intense bow echo raced eastward at 55-60 kts into western Hardin county producing severe wind damage. Highest reflectivity values along the leading edge indicated strong vertical ascent and a balance between the convective cold pool behind the gust front and the strongly-sheared environment. Also, a slight reflectivity notch existed at 0.5 deg on the bow's leading edge near the Hardin/Meade border, where SRM data showed the possible genesis of another vortex, especially above 0.5 deg. Thus, this location deserved particular attention.

0623 UTC Tornado Central/Northern Hardin

-Radar data was limited at 0623 UTC. However, the bow apex was bulged out significantly at 1.5 deg across central Hardin county. A close inspection of the 50 dBZ returns along the apex showed a small inflow notch along and just north of the apex where reflectivity values were slightly lower. An intensifying and more organized cyclonic circulation was coincident with this notch. Mesocyclone and tornado development are common along and just north of the apex of an organized bow echo within a dynamic, sheared environment. With strongly supportive evidence in radar data, the severe thunderstorm warning should be upgraded to a tornado warning for the northern half of Hardin county, with continued emphasis that very strong straight-line winds also will accompany the squall line. To the north, a cyclonic circulation still was evident across eastern Meade county, although V_r values began to decrease. This circulation's V_r cross-section is shown at right (values in kts); the T and neighboring bold line indicate the period a tornado occurred.



0633 UTC Tornado Bullitt
Severe Nelson, Larue

-By 0633 UTC, the intense bow echo was along the Hardin-Bullitt county line, just southeast of the RDA. A well-defined moderate-to-strong cyclonic circulation (V_r of 40-45 kts) existed just north of the apex over northeastern Hardin county. The circulation extended into storm's middle levels and appeared to tilt forward with height. A portion of this tilt may be attributable to fast system movement versus the volume scan time interval. Radar trends continued to justify the issuance of a tornado warning for Bullitt county. The bow also was approaching Nelson and Larue counties rapidly, requiring a strongly worded severe thunderstorm warning, especially for Nelson county.

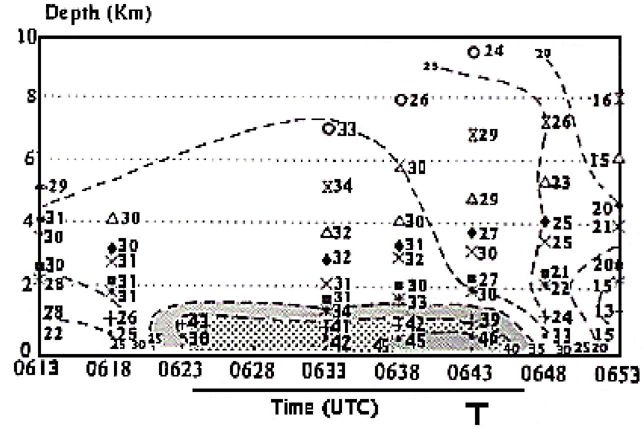
-The orientation of the entire squall line versus its movement also was important. The northern/eastern part of the line was oriented north-south, i.e., normal to its eastward movement, a relationship that favors wind damage. Conversely, the southwestern part of the line was oriented east-west, i.e., nearly parallel to system movement, a relationship that decreases strong wind potential but increases cell training and heavy rainfall potential. The outflow boundary in this area was just south of the convection across southern Breckinridge and northern Grayson counties. Animated reflectivity imagery and radar precipitation estimates should be monitored closely in this area.

0643 UTC

-At 0643 UTC, straight-line wind damage was occurring over western Nelson and Larue counties. Across Bullitt county, a well-defined line echo wave pattern (LEWP) was evident in the highest reflectivity values, indicating high tornado potential just north of the bow apex. A weak echo channel (WEC) also existed over extreme southern Bullitt and northeastern Hardin counties at 0.5 deg, a signature often associated with a locally-enhanced rear inflow jet (RIJ). SRM data verified that higher wind speeds were coincident with the WER, resulting in damage along the leading bow apex. A small, but intense cyclonic circulation also was noted at 0.5 deg over southern Bullitt county (inbound velocities most prominent) just north of the apex. An F1-F2 tornado occurred at this location. Finally, two air streams apparently were present within the MCS. Low-level storm-relative outbound velocities were noted over Hardin, western Larue and Nelson, and southern Bullitt counties. However, at higher altitudes (e.g., 10.0 deg elevation), inbound winds appeared over these areas, suggesting storm-relative front-to-rear flow overtop the low-level rear-to-front flow. The strongest inbound velocities at 10.0 deg may signify the location of the intense convective updraft zone. Meanwhile, heavy rain was occurring over Hardin, southern Breckinridge, and northern Grayson counties north of the outflow boundary. Precipitation amounts and duration should be monitored for flood potential.

0648 UTC Severe Spencer

-The bow echo continued to track eastward rapidly toward Spencer county at 0648 UTC, where a severe thunderstorm warning was required. The storm-scale frontal structure (LEWP) had become a little less pronounced, while the tornado-producing vortex weakened across southeastern Bullitt county at 0.5 deg. A V_r cross-section of this circulation is shown at right, including the time period a tornado existed. Nevertheless, wind damage continued across extreme eastern Bullitt county. The greatest damage at this time was across Nelson county, associated with a well-defined WEC and maximum rear-to-front



flow. A new vortex also was developing in western Nelson county along the apex, just south of the previous circulation, a tendency that has been noted for other organized, dynamic bow echoes. Elsewhere, very heavy rain continued over Hardin, southern Breckinridge, northern Grayson, and Ohio counties.

0658 UTC	**Severe**	**Washington, Marion**
	Tornado	**northeastern Nelson**
	Flash Flood	**Hardin, southern Breckinridge, northern Grayson, eastern Ohio**

-A severe thunderstorm warning was required (at 0653 UTC) for Washington and Marion counties ahead of the bowing segment. Within the line, a cyclonic circulation, although not particularly tight, apparently existed in western Spencer county, coincident with a broad inflow zone north of the apex. Radar trends suggested that an upgrade to a tornado warning should at least be considered, although no tornado occurred there. Over northern Nelson county, an enhanced pulse of rear inflow (red outbounds) was coincident with a WEC on reflectivity data. Moderate-to-strong storm-relative inflow also was present resulting in a strong shear zone along and just north of the bow apex. Given radar trends and a more favorable reflectivity pattern, an upgrade to a tornado warning for northeastern Nelson county appears prudent.

-Meanwhile, cell training and very heavy rain persisted over Hardin, southern Breckinridge, and northern Grayson counties on the southwest portion of the squall line. Additional heavy rain was likely as the line would only sag slowly southeastward. Radar-estimated rainfall amounts were 1.5-2 inches (as shown on the 0703 UTC one-hour precipitation product) in this area. Thus, a flash flood warning appeared necessary or at least needed close consideration for these counties. Ground truth reports obviously would be helpful to assess flood potential.

0708 UTC	**Severe**	**Anderson, Mercer, Franklin**

-By 0708 UTC, the bow echo approached Anderson, Mercer, and Franklin counties. A tight reflectivity gradient still existed, but slightly less tight than earlier in the bow's life span across Breckinridge and Hardin counties. Thus, while strong straight-line winds still were likely (speeds were estimated up to 75 mph), winds were lower than those associated with the initial intense downburst and bow echo formation, when speeds were estimated up to 120 mph. In addition, the LEWP structure at 0708 UTC was less pronounced than earlier in the bow's evolution, although a subtle inflow notch appeared in southeastern Spencer county. A weak low-level circulation existed in this area, although no well-defined moderate-to-strong vortices were noted. As a result, radar trends suggested that a severe thunderstorm warning was sufficient at this time. No tornadoes were reported in this area.

-Cell training continued to dump very heavy rain over Hardin, southern Breckinridge, northern Grayson, and eastern Ohio counties. The convection remained slightly "elevated" above the low-level outflow boundary with 50 dBZ echoes extending well up into the storms. In fact, a 60-65 kg/m^2 VIL and 50,000-55,000 foot echo top was present at 0708 UTC over Grayson county. Thus, hail was possible in this cell, although the local environment likely was saturated and *VIL density* values (VIL ÷ ECHO TOP) were only about 3.5-3.7, borderline for large hail potential. No large hail was reported in Grayson county. Instead, the high echo top and large VIL value was indicative of torrential rain and possible flooding.

0718 UTC	**Severe**	**Boyle**

-Boyle was the next county in the path of the bow echo, as elevated front-to-rear storm-relative flow (green inbound velocities) remained above low-level rear-to-front flow (red outbounds). Meanwhile, moist, southerly environmental inflow continued to overrun the low-level outflow boundary producing very heavy rain. The highest cloud tops and VIL values were located over eastern Grayson and southern Hardin counties at 0718 UTC, within the flash flood warning area.

0728 UTC	**Severe**	**Woodford, Jessamine, Garrard**
	Flash Flood	**Larue**

-At 0728 UTC, a tight low-level reflectivity gradient was noted across Mercer and northwestern Boyle counties. A WEC across western Anderson county remained coincident with radar-detected enhanced elevated rear inflow. Thus, a severe thunderstorm warning was justified for the next set of counties in the path of the squall line, i.e., Woodford, Jessamine, and Garrard counties in east-central Kentucky.

-On the southwestern portion of the line, heavy rain continued to train eastward across several counties. Highest echo tops and VIL values were located over Larue county at this time, where heavy rain had been falling for at least 30 minutes and likely would continue for another 30-60 minutes. One-hour radar-estimated rainfall amounts ending 0723 UTC showed 1.5-2 inches per hour. Thus, a flash flood warning should be strongly considered or issued for Larue county, with warnings continued for those earlier issued counties.

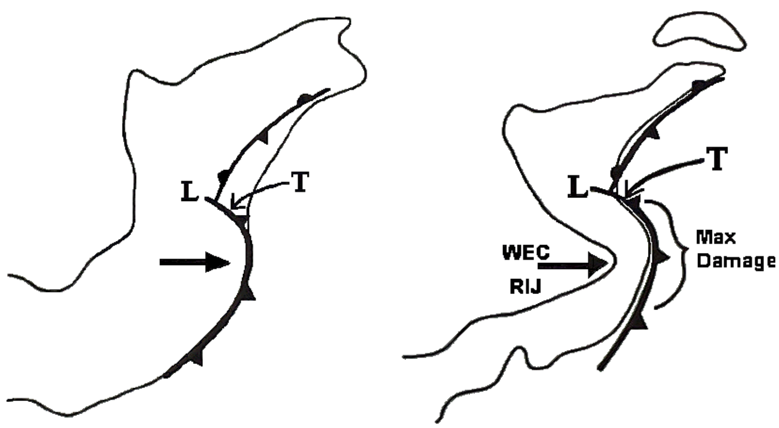
-After 0728 UTC, the bow echo continued to track eastward quickly producing additional wind damage, while the southwestern portion propagated slower producing flash flooding over several counties in central Kentucky.

QUESTION SHEET 2

1. ***Review 0.5 deg base velocity and reflectivity data at 0618 UTC. Explain what is occurring in base velocity data versus the corresponding reflectivity image.***

Base velocity data at 0618 UTC was deceptive compared to the corresponding reflectivity image. In particular, severe north-westerly winds were occurring across southern Breckinridge, western Hardin, into northern Grayson counties behind the leading edge of the intense bow echo. However, since these winds were directed normal to the radar beam (radar located in extreme northern Hardin county), base velocity data showed near zero velocity. Conversely, detected winds were over 50 kts across Hancock county, as winds there were better sampled by the radar. Just ahead of the zero area, a narrow zone of inbound velocities represented environmental south or southwesterly flow ahead of the squall line. Thus, potential shortcomings of single Doppler radial velocity data must be understood during the analysis process. The data also should always be compared to reflectivity to substantiate displayed signatures. At this time, base velocity data obviously mis-represented actual conditions. Elsewhere, a cyclonic circulation was evident across southern Meade county coincident with the intersection of the east-west axis of convection and the northern end of the bow echo.

2. ***Based on the 0643 UTC 0.5 deg base reflectivity image, sketch below an area that represents/outlines the yellow (>35 dBZ) returns. Next to this sketch, also sketch the area that outlines the highest reflectivity values (>45-50 dBZ) in the eastern portion of the MCS (i.e., the bowing segment). Do you note much difference in your 2 sketches? Finally, label on your second sketch of highest returns, likely locations for storm-scale frontal boundaries, storm-scale low or inflection point, cyclonic circulations and tornadoes, the rear inflow jet, weak echo channel, and location of maximum wind damage.***



The sketch of >35 dBZ returns (far left) shows broadly curved convection associated with the bow. However, the sketch of highest returns (>45-50 dBZ; near left) shows a much more pronounced convective-scale low and frontal (LEWP) structure. A small-scale low (L) may be located near the inflection point, with a warm or stationary boundary extending northeast from this point, and a cold (gust) front bulging south from the low. The low/inflection point is positioned within a strong cyclonic shear zone between the maximum rear inflow (RIJ) behind the line, coincident with a weak echo channel (WEC), and storm-relative inflow of high equivalent potential temperature air ahead of the line. In well-defined, dynamic LEWP structures, cyclonic circulations/mesocyclones and tornadoes (T) are common just north of the bow apex and area of maximum wind damage, usually near or just southeast of the inflection point low center or comma head. The sketch at left obviously suggests wind damage along the gust front, although closer inspection and identification of small-scale frontal structure within squall lines (near left sketch) are crucial to assessing tornado potential within bow echoes.

3. ***Again based on the 0643 UTC 0.5 deg base reflectivity image, briefly discuss the importance of the orientation of the convection in the western/southwestern portion of the MCS to the convection's direction of movement and to the location of the convective outflow boundary. What is the main hazardous weather threat in this area?***

The convection in the southwestern portion of the squall line was aligned nearly parallel to its direction of movement and just north of the outflow boundary across southern Hardin and Grayson counties. This relationship increases the potential for cell training and prolonged heavy rainfall, as individual cells within the line propagate over the same locations. Flash flooding also is a threat, especially given antecedent moist soil and high stream conditions. Moist, unstable low-level inflow was rising over the outflow boundary resulting in slightly "elevated" convection. Heavy rain and possible flooding were the main threats in this area. Hail also can occur with elevated storms, although significant wind damage is less likely. In contrast, the bow echo portion of the squall line was oriented nearly perpendicular to its direction of movement, a relationship that favors wind damage and brief heavy rainfall.